

A search for the “hopeless”: neutrinoless quadruple beta decay *and other $\Delta L > 2$ violating processes*

Pawel Guzowski
The University of Manchester

Fermilab NPC Seminar – 19th September 2019

Why the pessimistic title?

PHYSICAL REVIEW D **98**, 015035 (2018)

$\Delta L \geq 4$ lepton number violating processes

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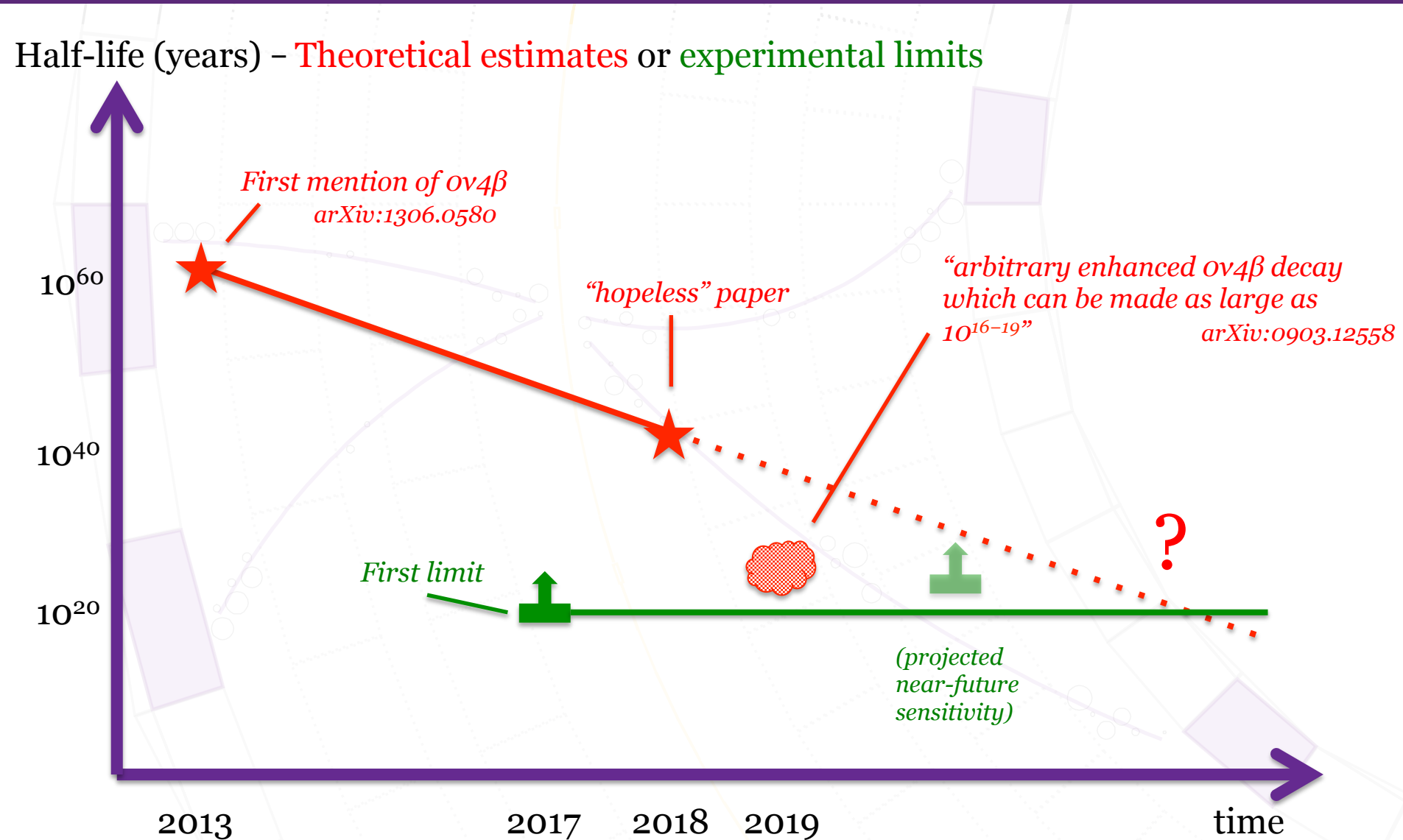
We discuss the experimental prospects for observing processes which violate lepton number (ΔL) in four units (or more). First, we reconsider neutrinoless quadruple beta decay, deriving a model independent and very conservative lower limit on its half-life of the order of 10^{41} ys for ^{150}Nd . This renders quadruple beta decay unobservable for any feasible experiment. We then turn to a more general discussion of different possible low-energy processes with values of $\Delta L \geq 4$. A simple operator analysis leads to rather pessimistic conclusions about the observability at low-energy experiments in all cases we study. However, the situation looks much brighter for accelerator experiments. For two example models with $\Delta L = 4$ and another one with $\Delta L = 5$, we show how the LHC or a hypothetical future pp collider, such as the FCC, could probe multilepton number violating operators at the TeV scale.

Paper from last year, a theoretical and phenomenological study of quadruple beta decay

Discussion of other processes being “*even more hopeless*” to observe than quadruple beta decay

Let us consider first the latter case, $\Delta B = 0$. This implies immediately that ΔL must be an even number. The relevant processes are then $0\nu(2n)\beta$ with $n > 2$. We discuss only β^- decays, since for quadruple beta decays it has been shown already in [15] that the positron emission or electron capture processes are **even more hopeless**, due to their smaller Q-values. For $0\nu(2n)\beta$ with $n > 2$ the same observation applies.

An extrapolation



Outline of this talk

- A couple of slides about double beta decay
 - not a large focus, given 4 is better than 2...
- Lepton number violation, implication for Dirac & Majorana neutrinos
- Quadruple beta decay phenomenology
- First ever search for quadruple beta decay
 - NEMO-3 experiment, analysis & result
- Future prospects & complementary searches

Neutrinoless double beta decay

- Already a relatively well known process

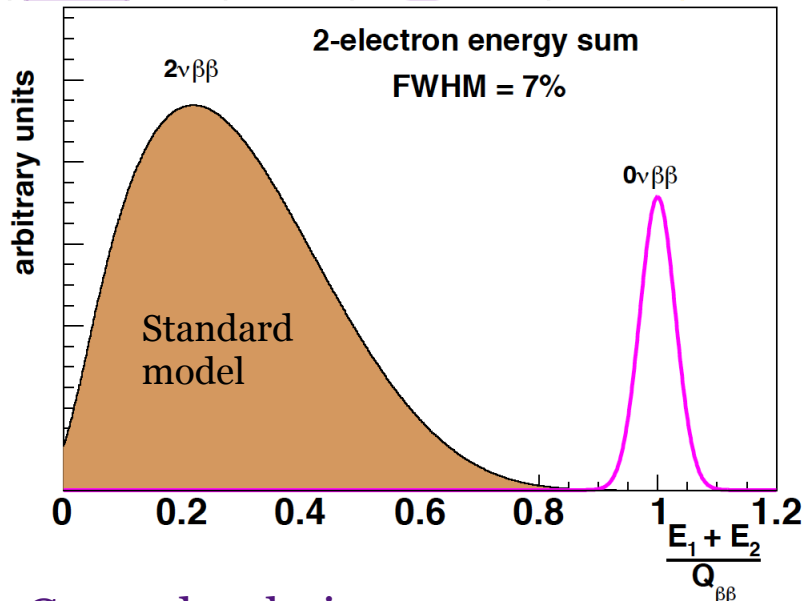
Date	Topic	Speaker	Files
Oct 19, 2017	Searching for neutrinoless double beta decay with EXO	David Moore, Yale	slides
Nov 30, 2017	Discovery probability of next-generation neutrinoless double-beta decay experiments	Giovanni Benato, UC Berkeley	slides
Apr 24, 2018	SuperNEMO and the mystery of matter	Cheryl Patrick, University College London	slides
Aug 1, 2018	Nausicaa's beach	Juan Jose Gomez Cadenas, Donostia International Physics Center (DIPC)	Slides
Dec 6, 2018	Search for new physics with neutrinoless double-β decay and the Ge-76 experimental program	Matteo Agostini, TUM Munich	Slides
Jan 10, 2019	Majorana or Dirac? That is the Question	Andre de Gouvea, Northwestern University	Slides
May 30, 2019	Search for neutrinoless double beta decay with CUORE	Stefano Dell'Oro, Virginia Tech	Slides

1 in 6 of the Seminars in the last two years

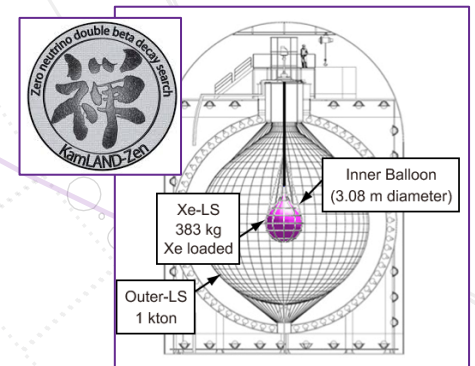
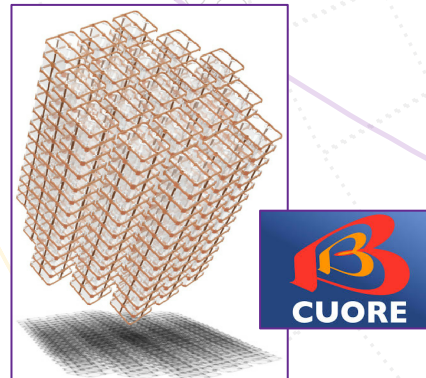
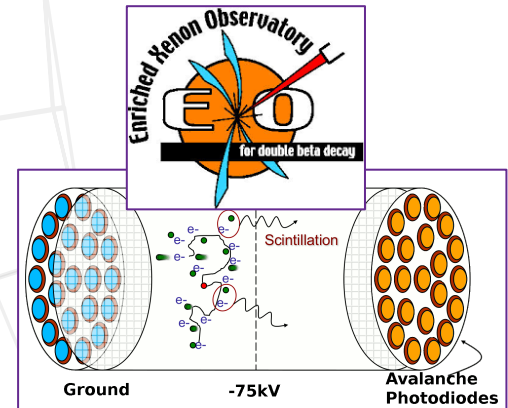
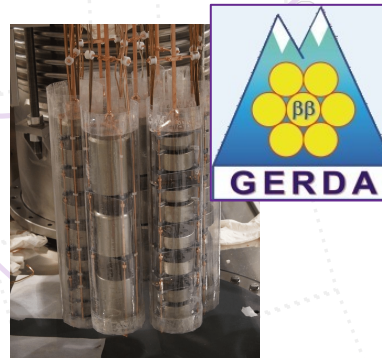
- So I will not discuss in a lot of detail

Homogeneous experiments

Most experiments are “homogenous” with their isotope embedded in their calorimetric detector, and only measure the decay energy



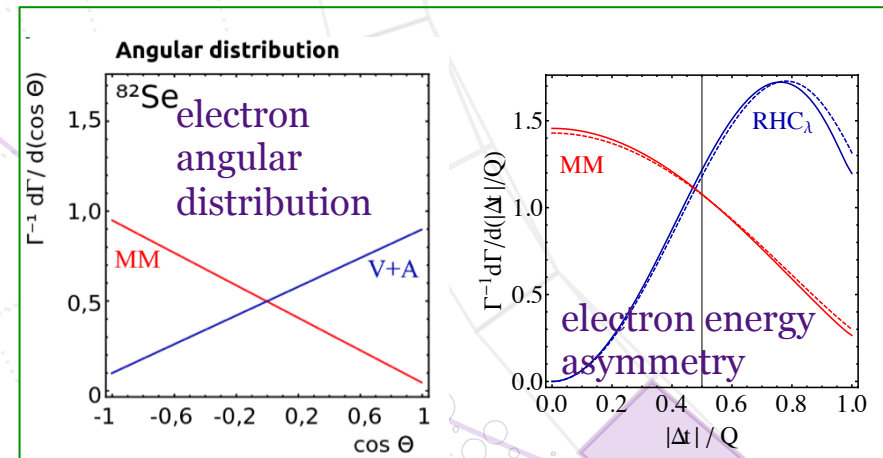
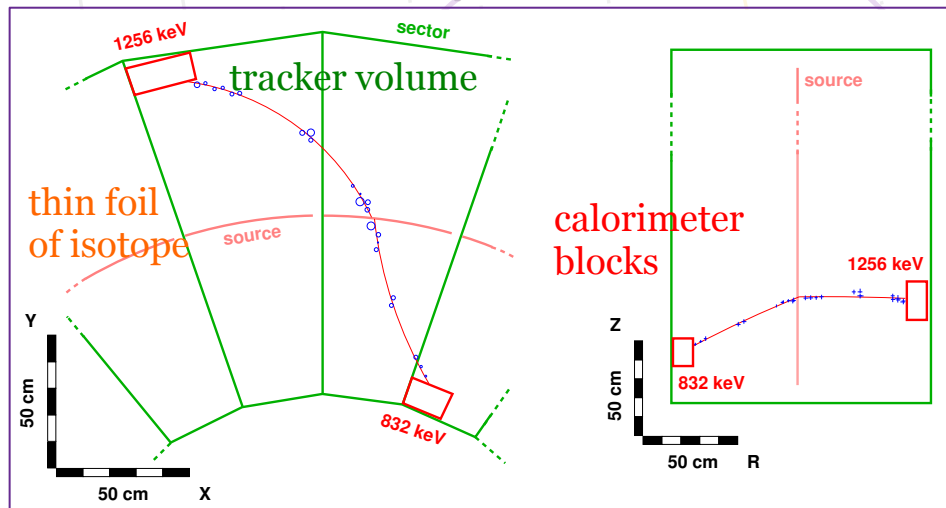
General technique: measure decay energy spectrum, search for bump at endpoint



apologies if your favourite experiment isn't mentioned

Heterogenous experiments

- NEMO-3 in contrast uses a tracker-calorimeter setup, with detector-independent isotope foils
 - Can detect the two electrons individually
 - Measure the kinematics of electrons to study **underlying mechanism**
 - Pay with poorer energy resolution & energy losses

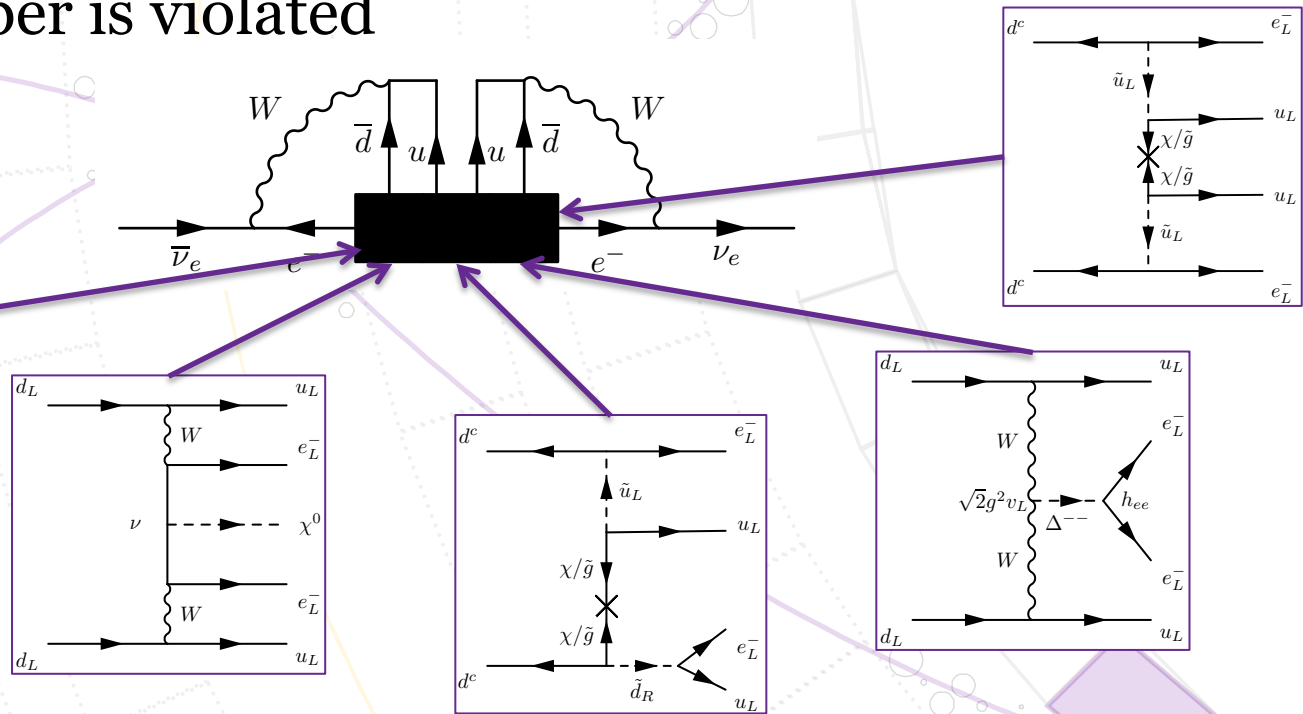


‘Standard’ majorana mass $0\nu\beta\beta$
 Right handed weak currents
 Eur.Phys.J.C70, 927 (2010)

Why theorists love double beta decay

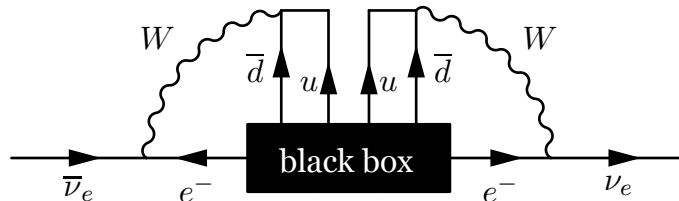
- Many new physics processes can contribute to neutrinoless double beta decay
 - All processes imply that neutrinos are Majorana and lepton number is violated

Examples including Supersymmetry, doubly-charged scalars, heavy neutral leptons, ...



Majorana models also good for explaining **leptogenesis** & **seesaw mechanism** neutrino mass generation

Black box theorem



Schechter, Valle (Phys Rev D 25,2951; 1982) state that:

- If neutrinos are Majorana fermions, then neutrinoless double beta decay **must occur** and lepton number is violated
- Likewise,
- If neutrinoless double beta decay occurs, it can slot into the **black box**, and neutrinos **must be** Majorana fermions
- *Does this apply if lepton number is generally violated ...?*

Lepton number violation

- “If lepton number is violated, then neutrinos have to be Majorana fermions”
 - By the black box theorem
- If neutrinos are Dirac fermions, can lepton number be violated?

Lepton number violation

- “If lepton number is violated, then neutrinos have to be Majorana fermions”
 - By the black box theorem
 - *not necessarily true...*
- If neutrinos are Dirac fermions, can lepton number be violated?
 - **YES!**

Lepton number violation

- “If lepton number is violated, then neutrinos have to be Majorana fermions”
 - By the black box theorem
 - *not necessarily true... only if by 1 or 2 units*
- If neutrinos are Dirac fermions, can lepton number be violated?
 - **YES!**
 - Has to be by ≥ 3 units

Leptogenesis with Dirac LNV

- Leptogenesis is the phenomenon whereby the baryonic matter-antimatter asymmetry of the universe is generated from a lepton number asymmetry
 - J Turner seminar – 18 Oct 2018
 - “Most theories of leptogenesis assume neutrinos are Majorana (*of course there are exceptions*)”
- One particular exception involving LNV Dirac neutrinos – J Heeck, Phys Rev D 88, 076004 (2013)

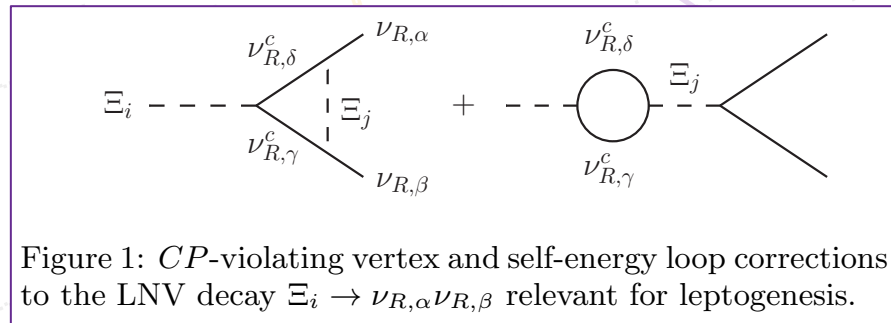
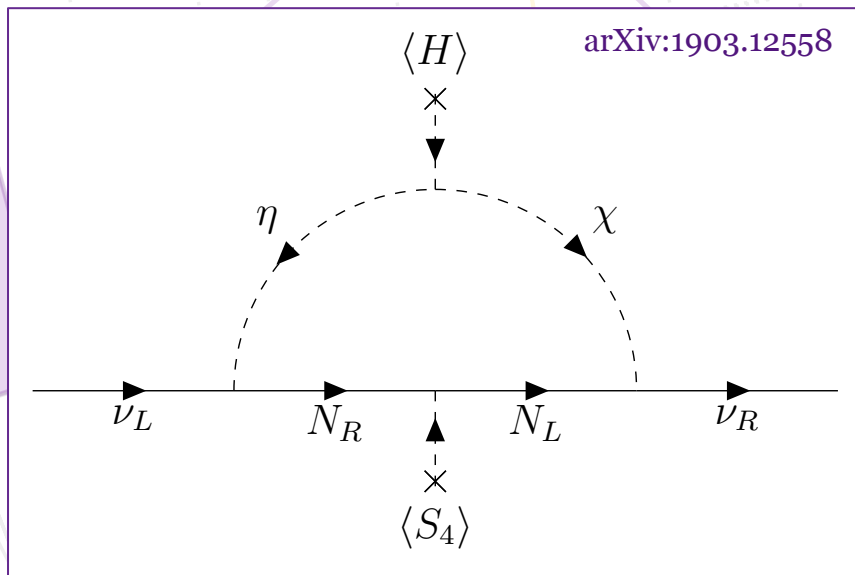


Figure 1: CP -violating vertex and self-energy loop corrections to the LNV decay $\Xi_i \rightarrow \nu_{R,\alpha} \nu_{R,\beta}$ relevant for leptogenesis.

Mass generation with Dirac LNV

- Dirac neutrino masses can be generated at the loop level – “radiative corrections”
 - see arXiv:1505.01738 for a review
- Usually introduce new scalar fields, at least one with a vacuum expectation value $\langle S \rangle$
 - If $\langle S \rangle$ carries a lepton number, LNV with dirac neutrinos is possible
- These models usually produce dark matter candidates as well



Seesaw mechanism,

$$m_\nu \propto 1/M_N$$

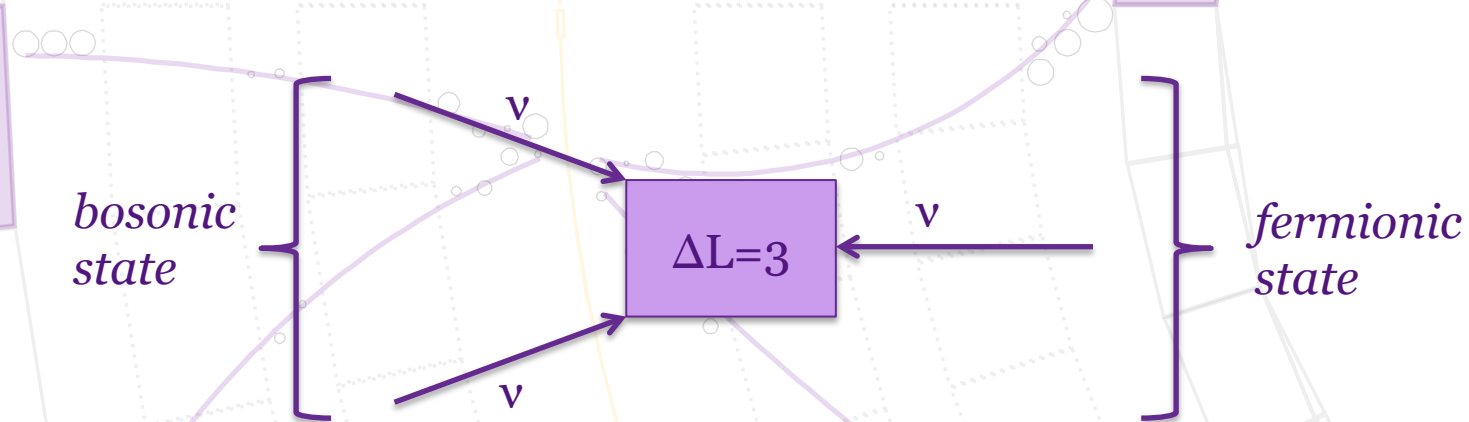
but with Dirac neutrinos

Why theorists should love Dirac LNV

- Dirac LNV models can be used to explain
 - Leptogenesis ✓
 - Neutrino mass generation ✓
 - Dirac/Majorana nature of neutrino ✓
 - In conjunction with non-observation of neutrinoless double beta decay
- How do you search for these models?
 - Neutrinoless n -tuple beta decays ($n > 2$)
 - Colliders production of intermediate states

Neutrinoless triple beta decay

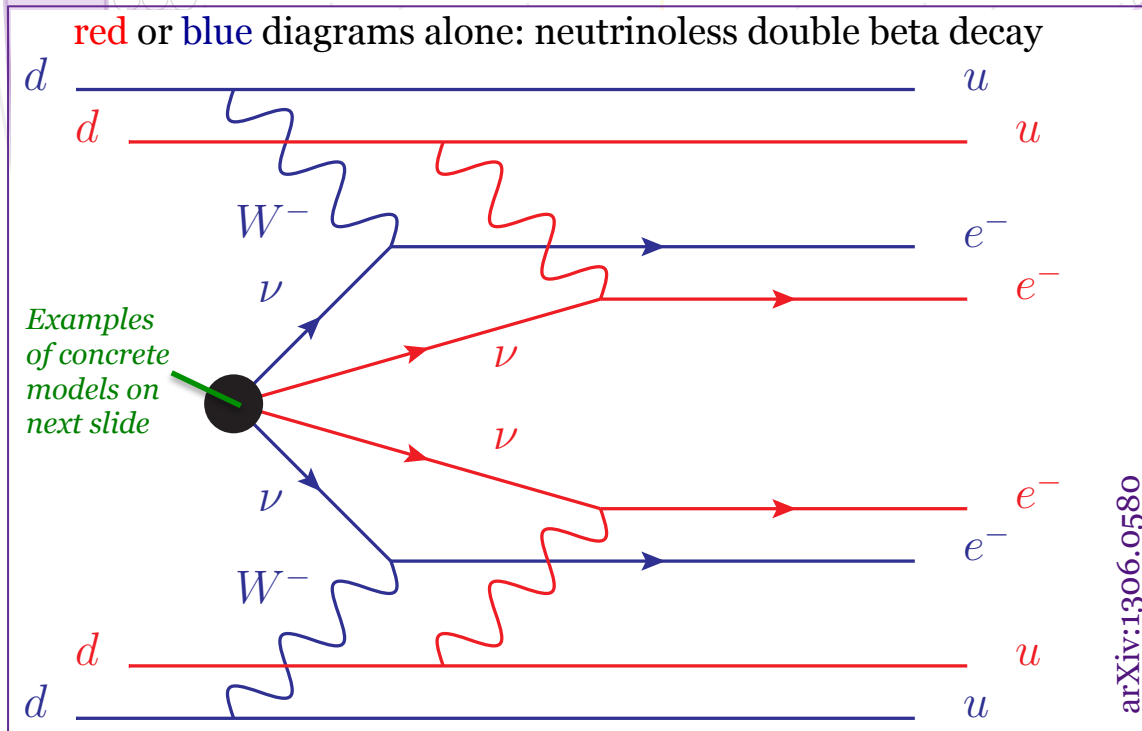
- Minimal Dirac-LNV scheme, with $\Delta L=3$
- However, it is **forbidden** by Lorentz symmetry



- Could include Baryon number violation as well, but then no longer “beta decay”
 - $\Delta B=1$ strongly constrained by nucleon decay searches

Neutrinoless quadruple beta decay

- Minimal Dirac-LNV scheme allowed by all symmetries: $\Delta L=4$

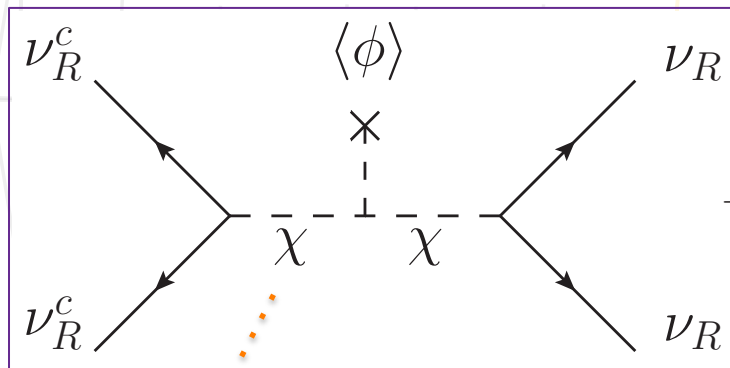


Inside nucleus, 4 neutrons convert to 4 protons (nucleus $Z \rightarrow Z+4$), and emit 4 electrons

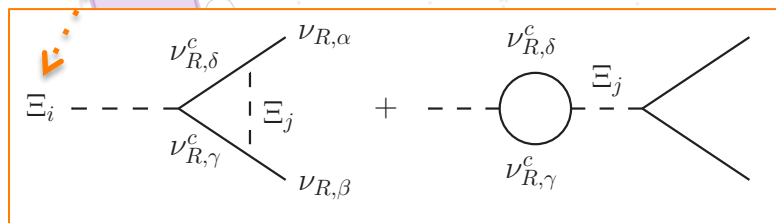
Sum of the energies of the 4 electrons is a constant (no neutrinos are emitted)

Some specific models

Heeck, Rodejohann
arXiv:1306.0580
“leptogenesis” model

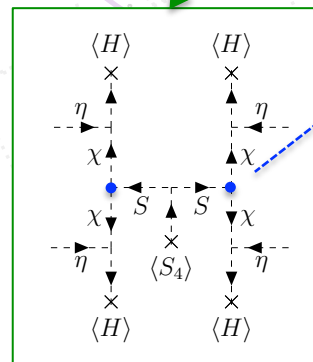
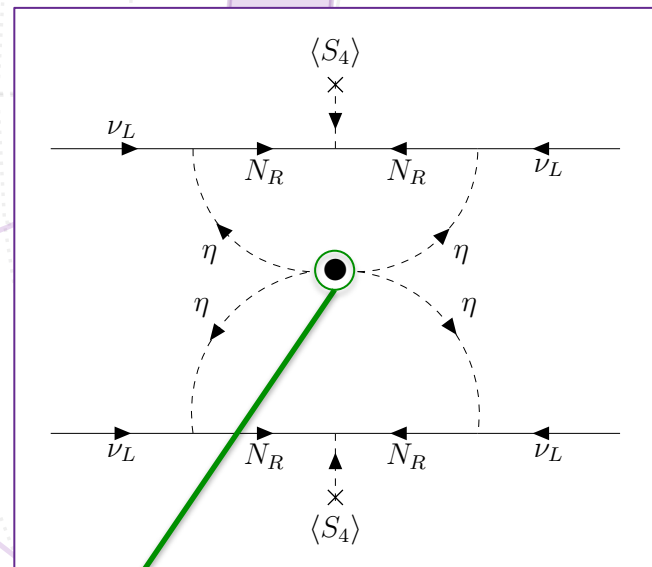


This model requires
helicity-flip,
suppressed by $(m_\nu)^4$
 $T_{1/2}$ estimate $\sim 10^{60}$ years



leptogenesis mechanism

Dasgupta, Kang, Popov
arXiv:1903.12558
“radiative Dirac mass” model



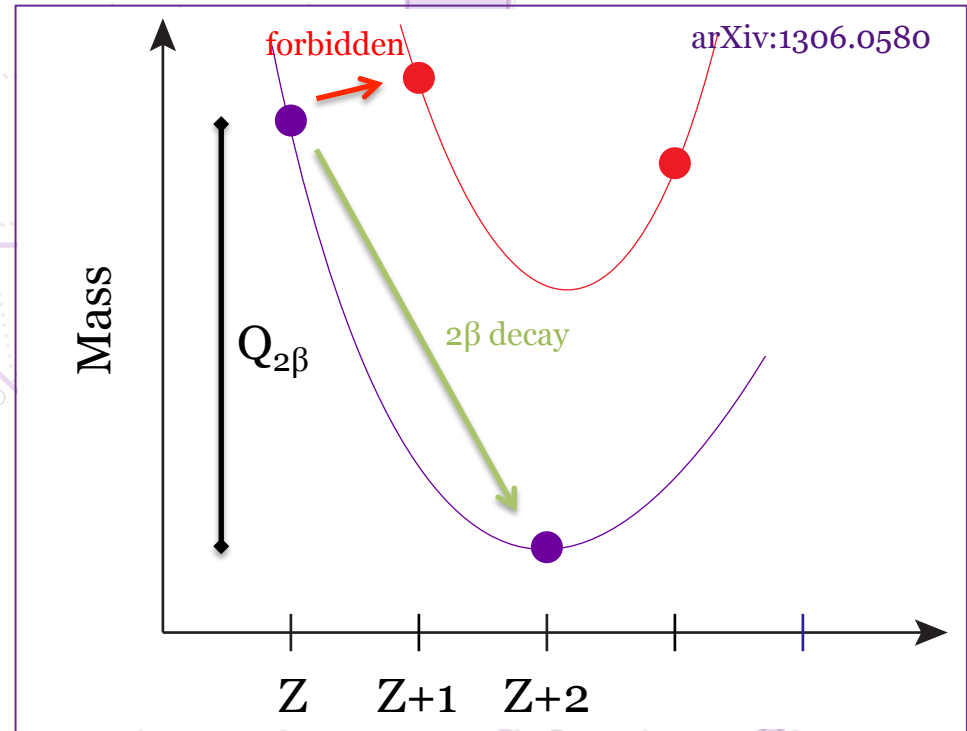
$S\chi\chi$ coupling only
constrained by
unitarity conditions;
could lead to 10^{16-19}
enhancements

Phenomenology

- So, models of neutrinoless quadruple beta decay exist
 - One particular encouraging model, linked to radiative Dirac neutrino mass generation, estimates an enhanced half-life even as low as $\sim 10^{22}$ years
- How should we search for neutrinoless quadruple beta decay?

What makes a good 4β isotope?

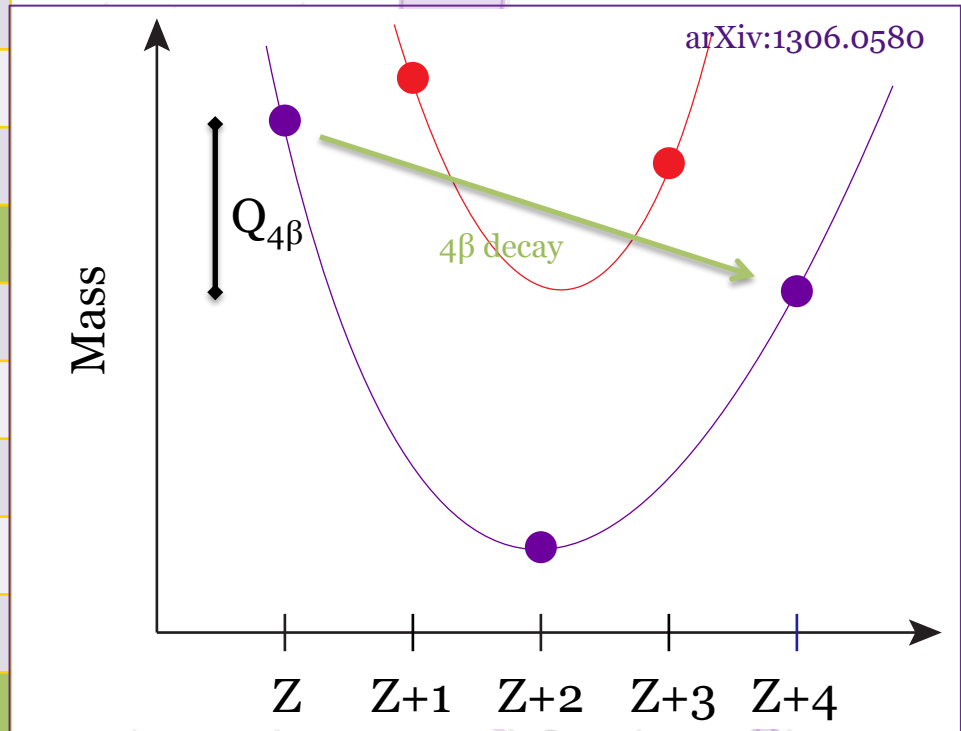
Isotope	$Q_{2\beta}$ (MeV)
^{48}Ca	4.27
^{76}Ge	2.04
^{82}Se	3.00
^{96}Zr	3.35
^{100}Mo	3.03
^{110}Pd	2.02
^{116}Cd	2.81
^{124}Sn	2.29
^{130}Te	2.53
^{136}Xe	2.46
^{150}Nd	3.37



What makes a good 4β isotope?

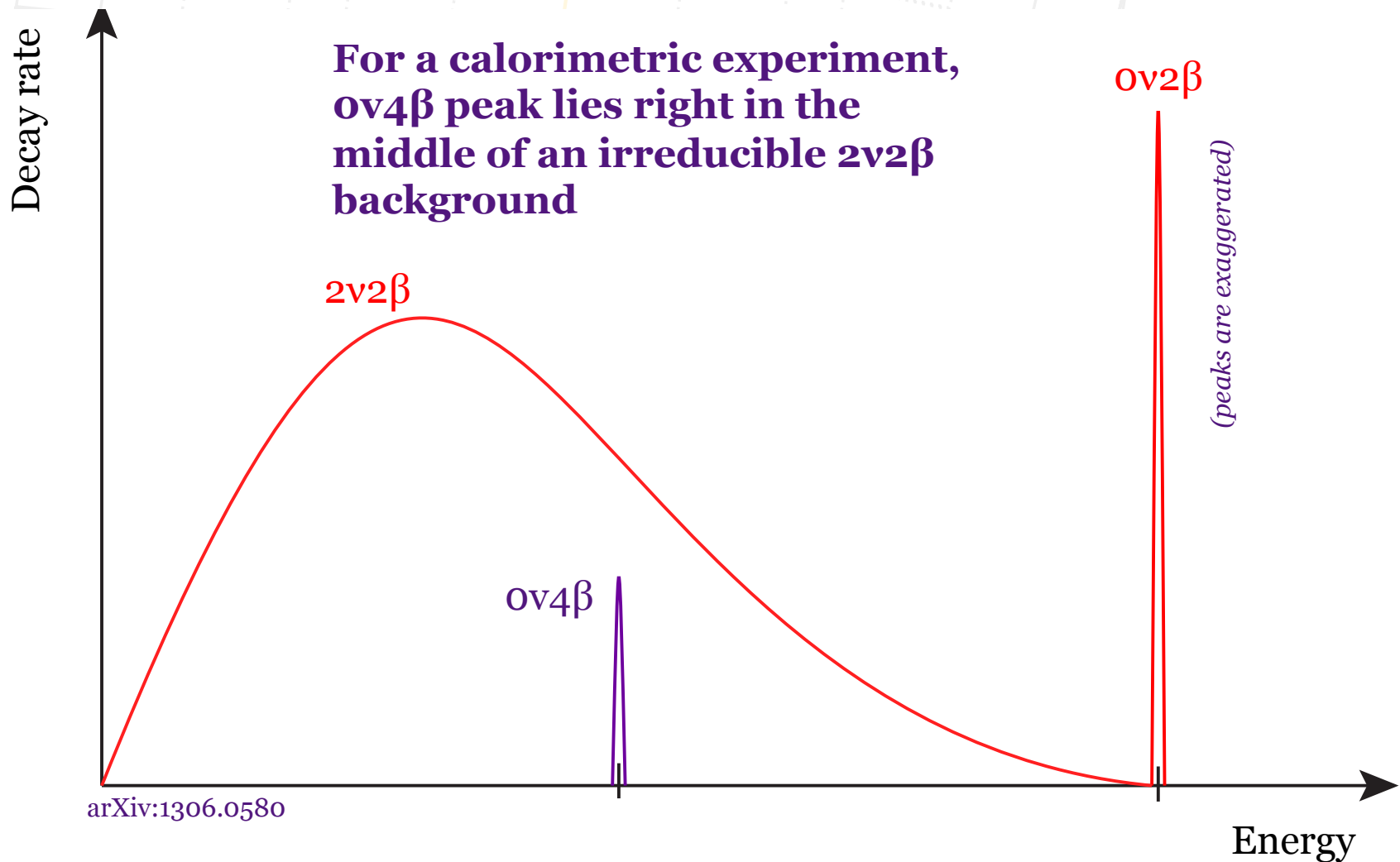
Isotope	$Q_{2\beta}$ (MeV)	$Q_{4\beta}$ (MeV)
^{48}Ca	4.27	×
^{76}Ge	2.04	×
^{82}Se	3.00	×
^{96}Zr	3.35	0.63
^{100}Mo	3.03	×
^{110}Pd	2.02	×
^{116}Cd	2.81	×
^{124}Sn	2.29	×
^{130}Te	2.53	×
^{136}Xe	2.46	0.04
^{150}Nd	3.37	2.08

(× = daughter isotope more massive)

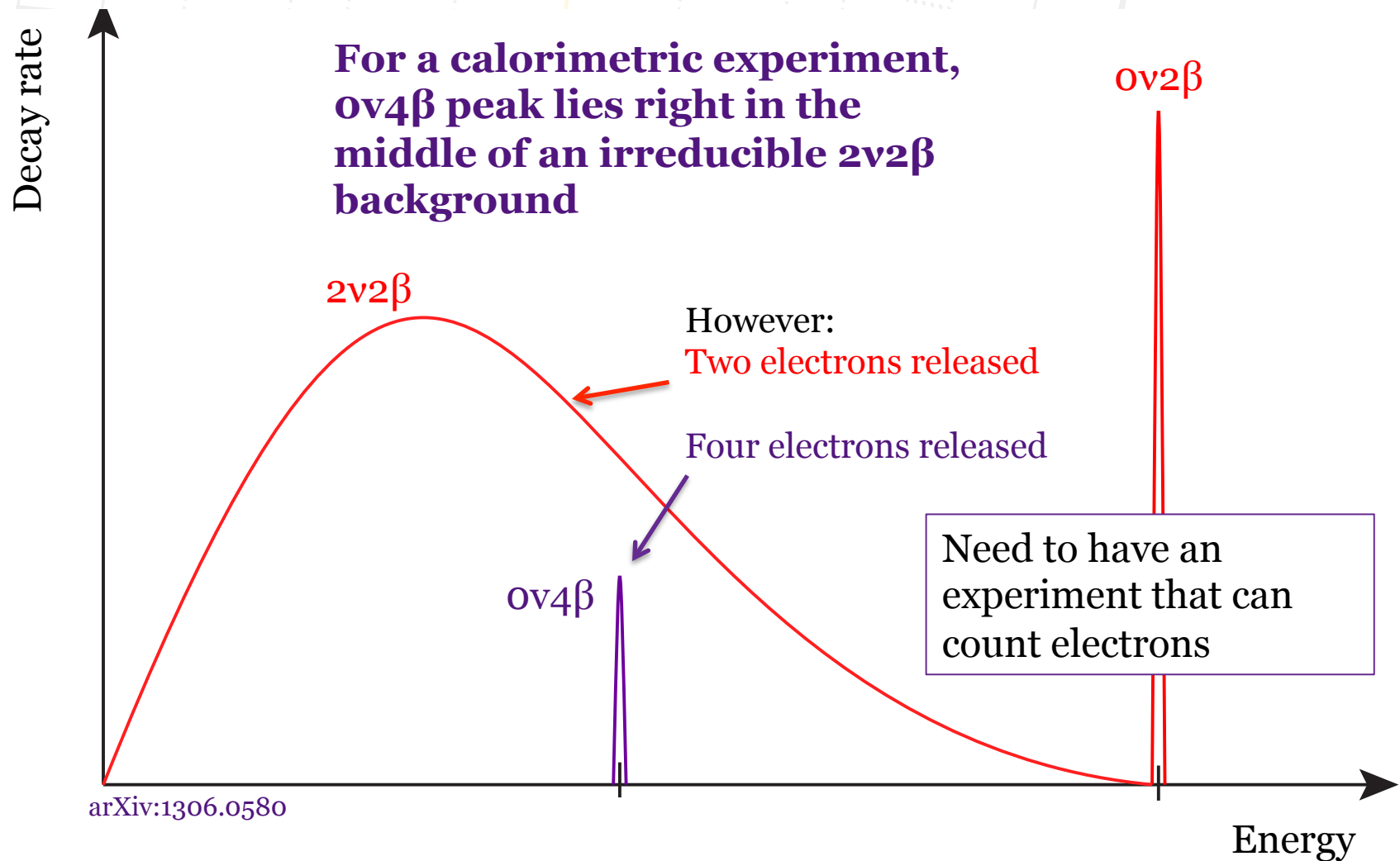


All 4β candidate isotopes are also 2β isotopes, but with lower Q-values

Expected energy spectrum



Expected energy spectrum



Designing an ideal experiment

- An ideal experiment would need to use ^{96}Zr or ^{150}Nd as the isotope of study
 - ^{136}Xe has a tiny Q -value (decay rate $\propto Q^{11}$)
- Would need to be able to count the number of electrons released in the decay

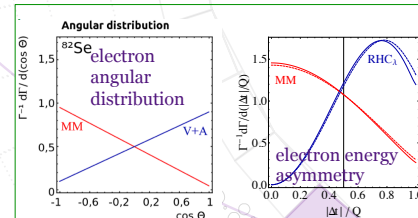
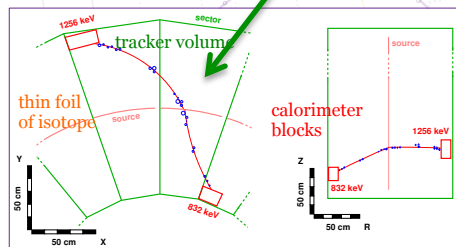
Designing an ideal experiment

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 - ^{136}Xe has a tiny Q -value (decay rate $\propto Q^{11}$)
- Would need to be able to count the number of electrons released in the decay
- Fortunately:

Several
minutes
earlier:

Heterogenous experiments

- NEMO-3 in contrast uses a tracker-calorimeter setup, with detector-independent isotope foils
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 - Measure the kinematics of electrons to study underlying mechanism
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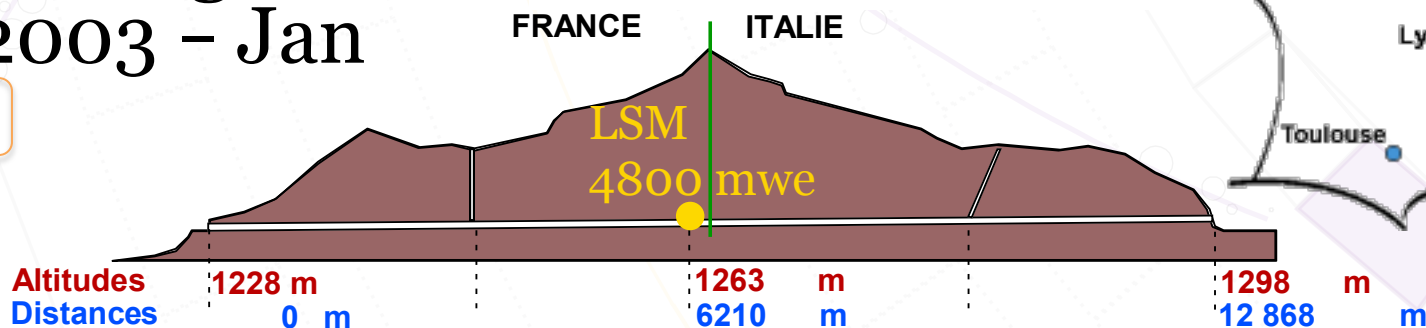
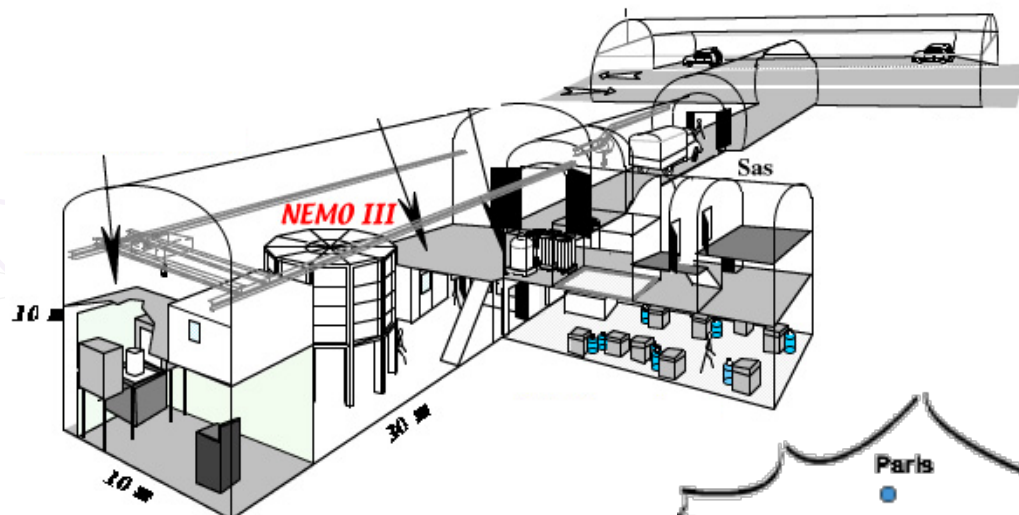


'Standard' majorana mass $\nu\bar{\nu}\beta\beta$
Right handed weak currents
Eur.Phys.J.C70, 927 (2010)

NEMO-3 experiment



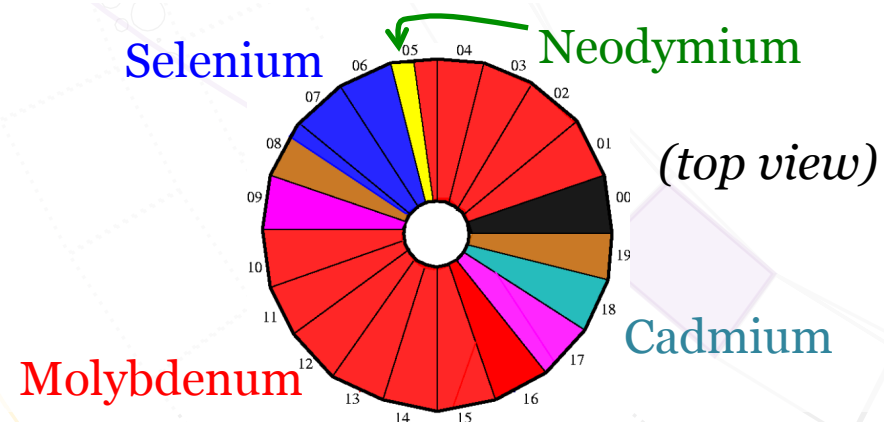
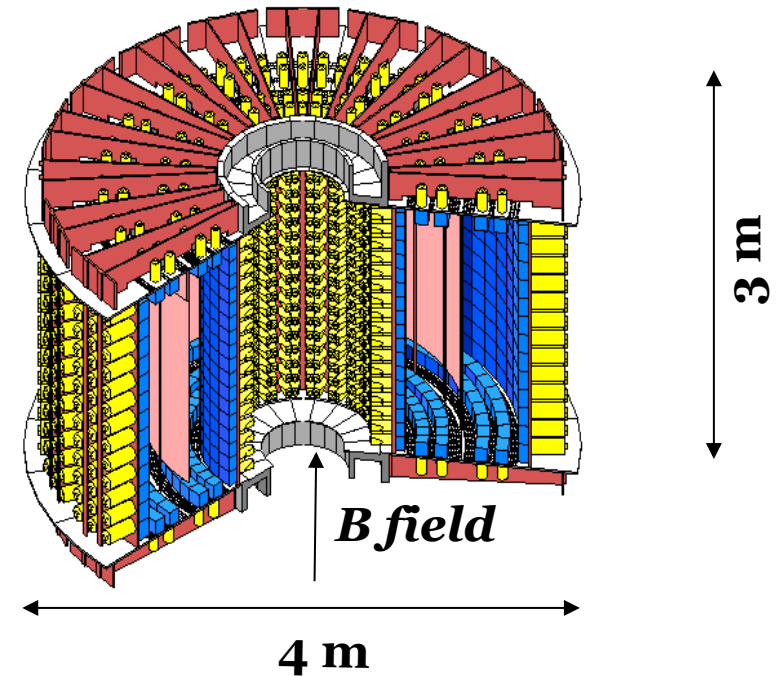
- 12 countries, 27 institutions
- Experiment was located in *Laboratoire Souterrain de Modane*
- Data taking from Feb 2003 – Jan 2011



reminder: ov4 β wasn't proposed until 2013

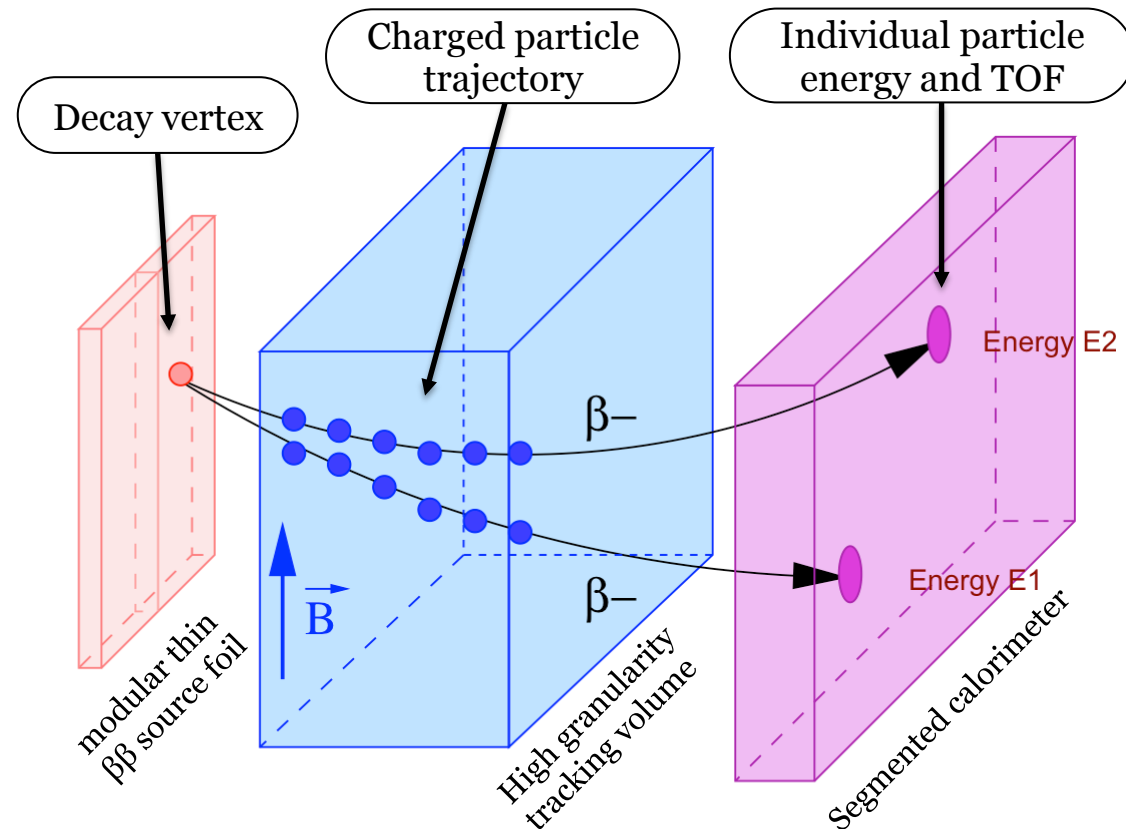
NEMO-3 detector

- **Source**
 - 10kg in total, 20m² area foils
 - 7kg ¹⁰⁰Mo, 1kg ⁸²Se
 - ¹¹⁶Cd, ¹⁵⁰Nd, ⁴⁸Ca, ⁹⁶Zr, ¹³⁰Te
 - 35 grams of ¹⁵⁰Nd
- **Tracker**
 - Drift wire chamber in Geiger mode
 - 9 layers/side, 6180 cells
 - 25G magnetic field
- **Calorimetry**
 - 1940 plastic scintillator blocks
 - 3", 5" low-radioactivity PMTs



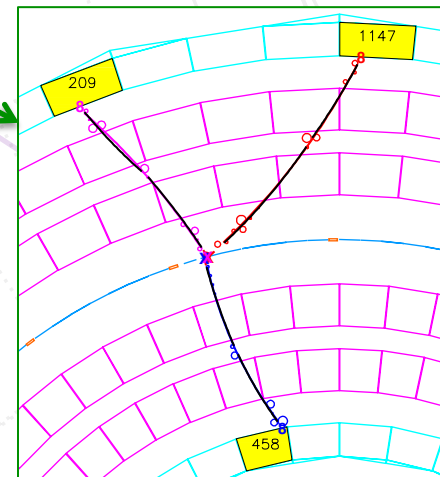
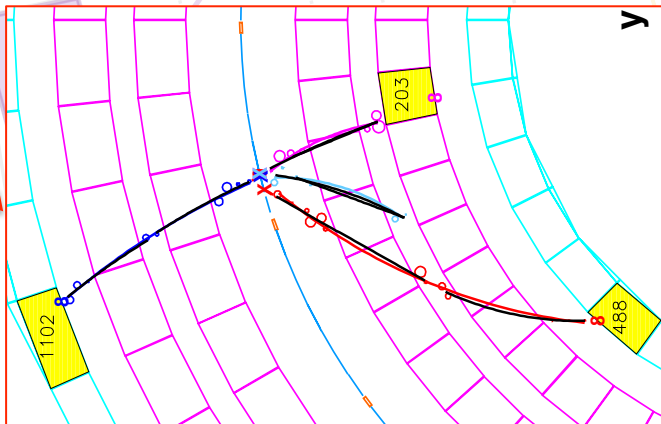
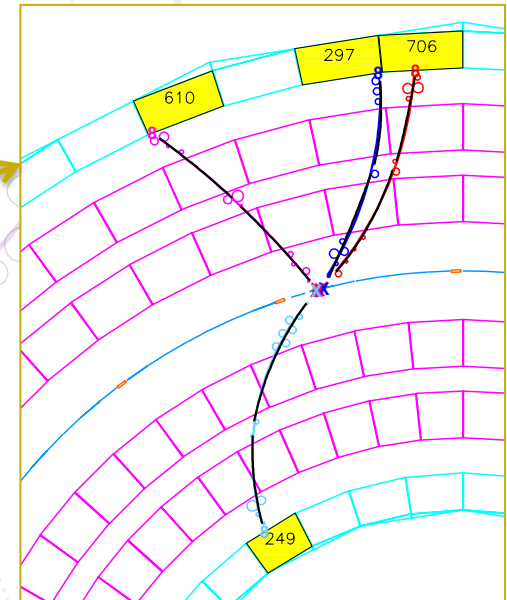
Detection principle

- **Calorimeters** provide E , t measurements
- **Tracker** used vertexing, charge ID, angles
- **PID**: e^- , γ , e^+ , α
- Knowledge of **full event topology** allows disentangling double-beta decay mechanisms
- All **backgrounds determined experimentally** in situ by exploiting topologies
 - (1 track, 1 track + N gammas, etc)



0v4 β event topologies

- Three event topologies were chosen to be studied
 - Only ^{150}Nd was used in this analysis
 - ^{96}Zr has too low a Q-value for efficient detection of the electrons
 - 4e (the golden channel): 4 visible electrons with an energy measurement
 - 3e1t: One of the four tracks doesn't have an associated energy measurement
 - 3e: only three visible electrons, all with an energy measurement
 - For signal events, one of the electrons has been absorbed in the source foil



Event selection

- Quality cuts applied to the events; relatively loose cuts to maximise efficiency
 - Minimum 150keV electron energy measurement
 - Timing of calorimeter hits consistent with decay originating in foil
 - Vertex distance cuts on the four tracks
 - No unassociated calorimeter hits
 - removal of gamma decays
 - No delayed tracks
 - removal of alpha decays

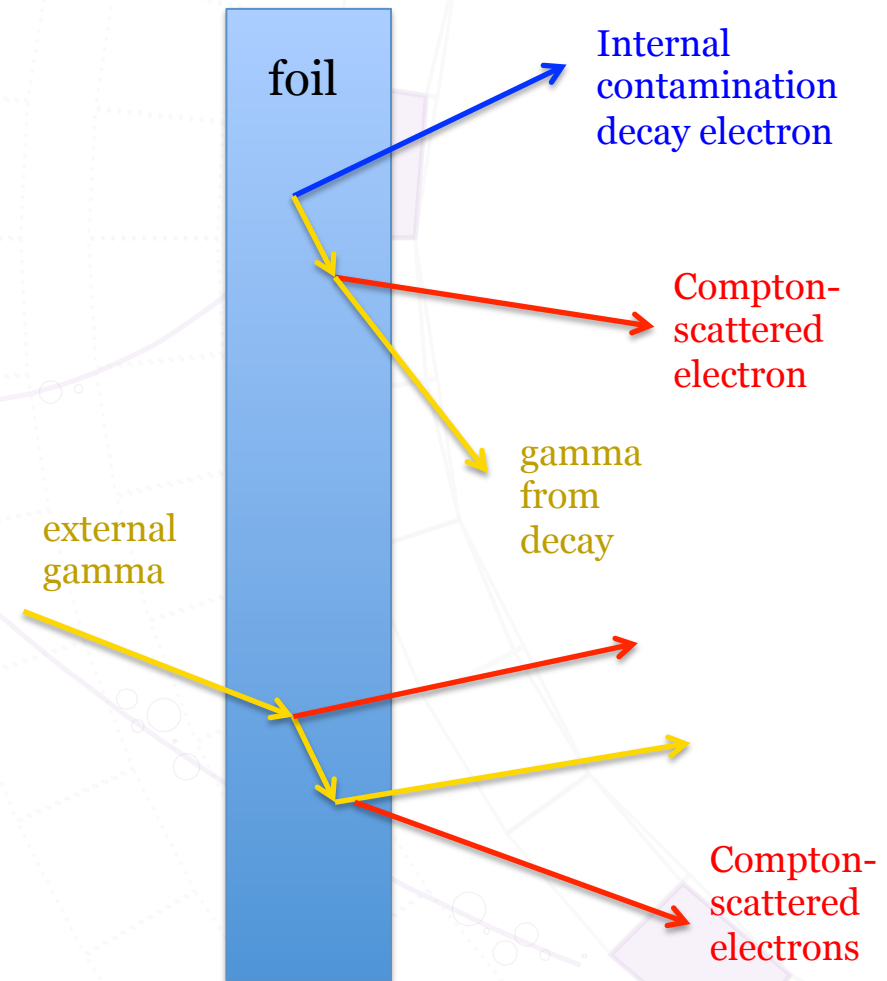
Topology	Efficiency
4e	0.2 %
3e1t	0.9 %
3e	3.6 %

Efficiencies (including topological acceptance)

Although the 3e channel isn't "golden", it has the highest efficiency, due to absorption of the low-energy electrons in the foil

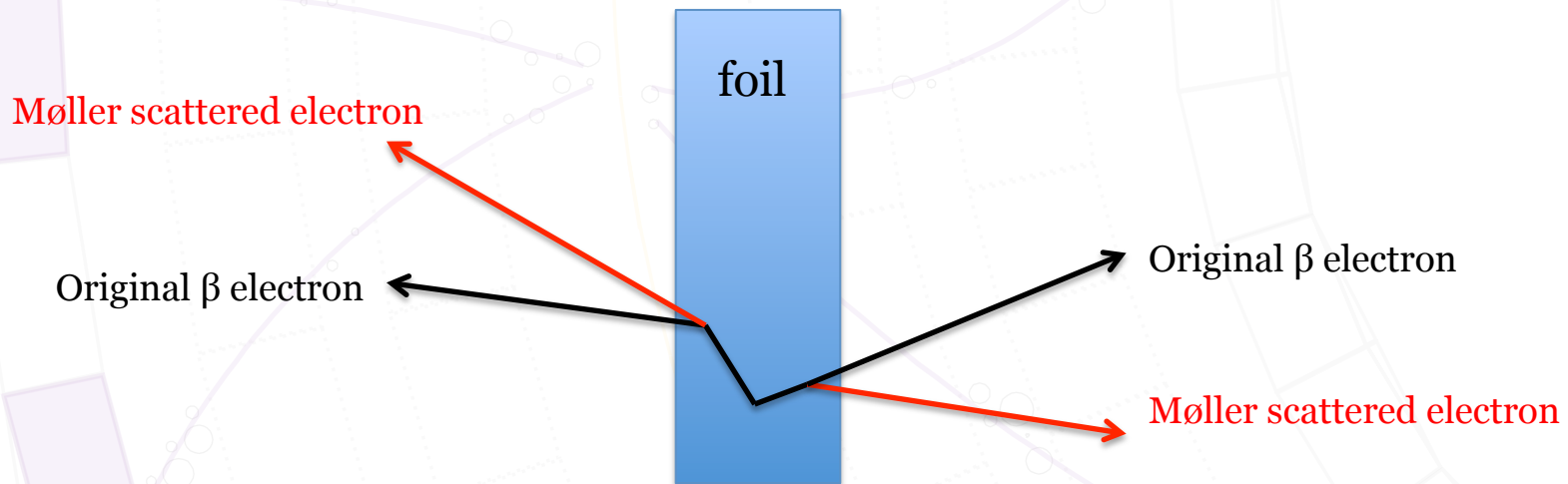
Backgrounds

- Backgrounds in common with the double-beta analyses
 - Internal contamination of the source foil
 - External contamination (radioactivity of detector components) inducing signal-like events
- All these background activities **measured in-situ** during the dedicated ^{150}Nd $2\nu 2\beta$ measurement
 - Phys Rev D 94, 072003 (2016)



Møller scattering

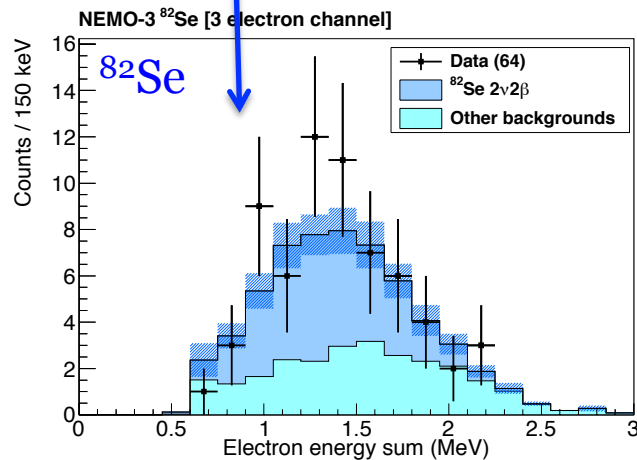
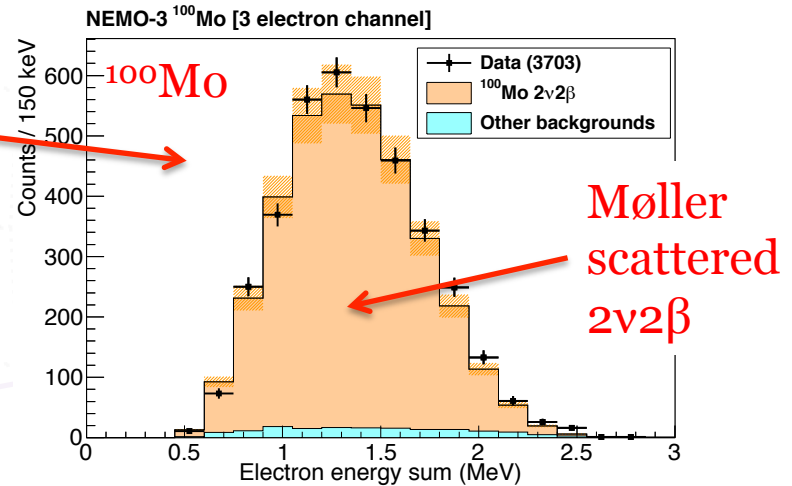
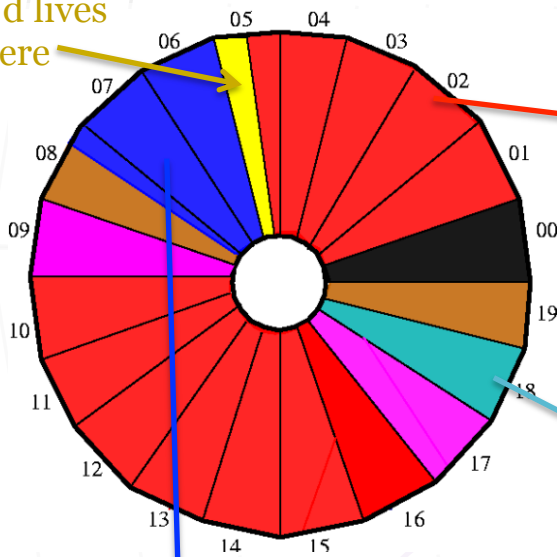
- A major background to this analysis is Møller scattering of $2\nu 2\beta$ electrons
 - Irreducible contamination (all 4β isotopes are also 2β emitters)
 - Reducible by having lower density foil
- Beta electrons travelling through the source foil can kick out another electron in the bulk of the material



- Any future experiments would benefit from thinner/less dense foil
 - Would also improve energy & electron losses
- We can check the background modelling using sidebands...

Sidebands: 4β -inert isotopes

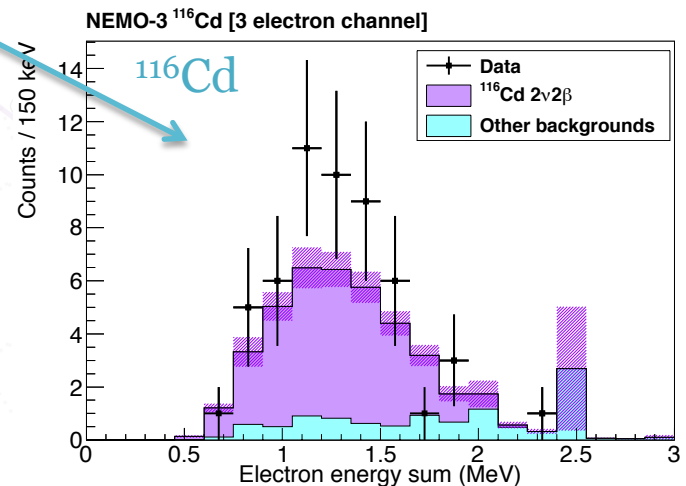
^{150}Nd lives
in here



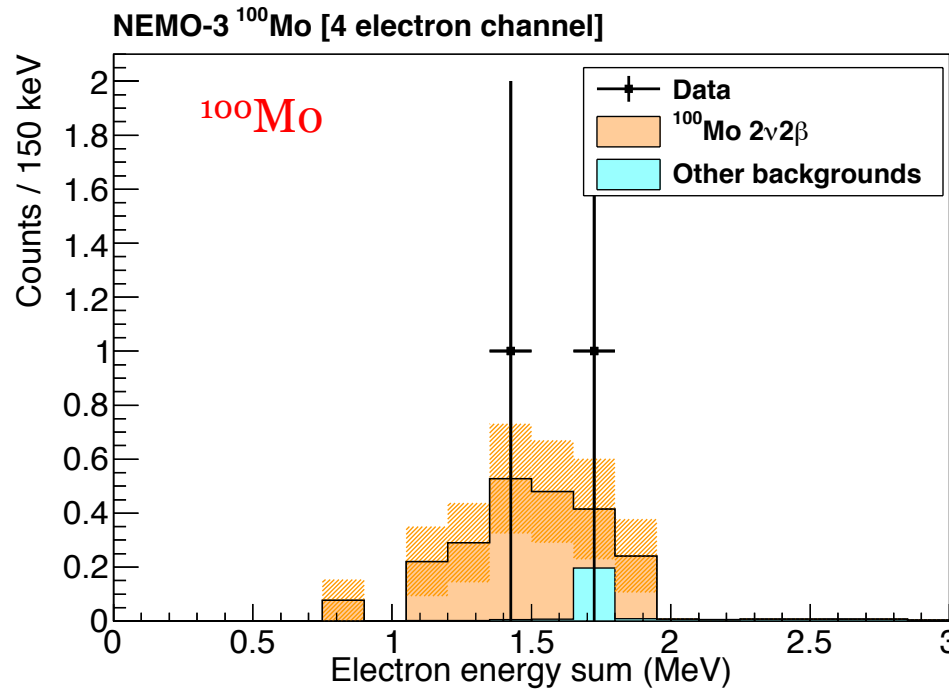
3e topologies

No fits
performed here

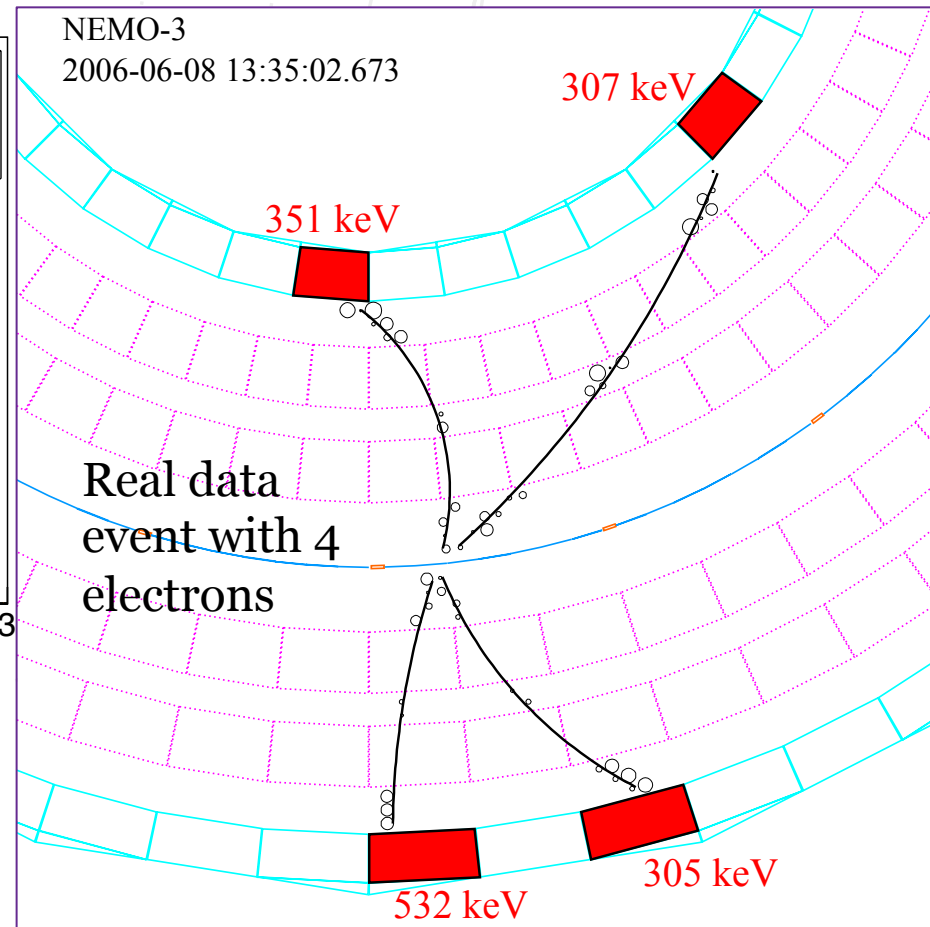
All activities
measured in
dedicated 2v2 β
analyses



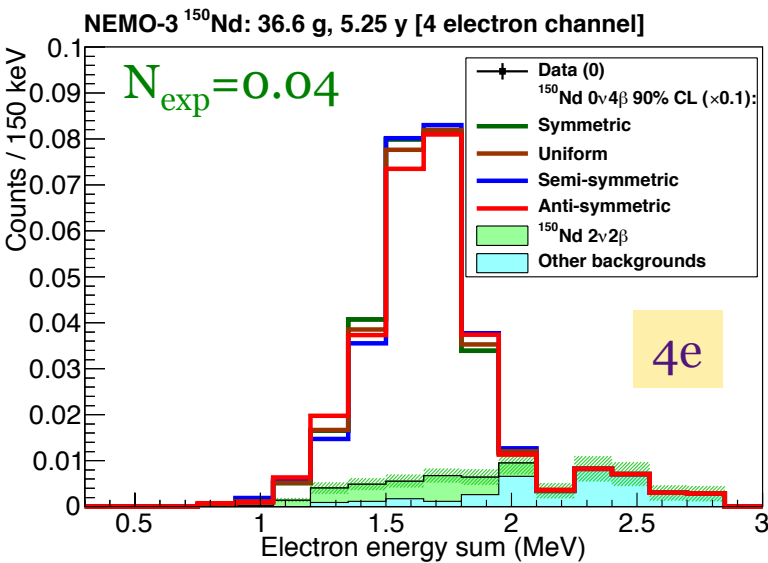
Golden channel sideband



- 2.3 events expected
- 2 observed
- Sideband cross-checks gives us confidence that the backgrounds are under control

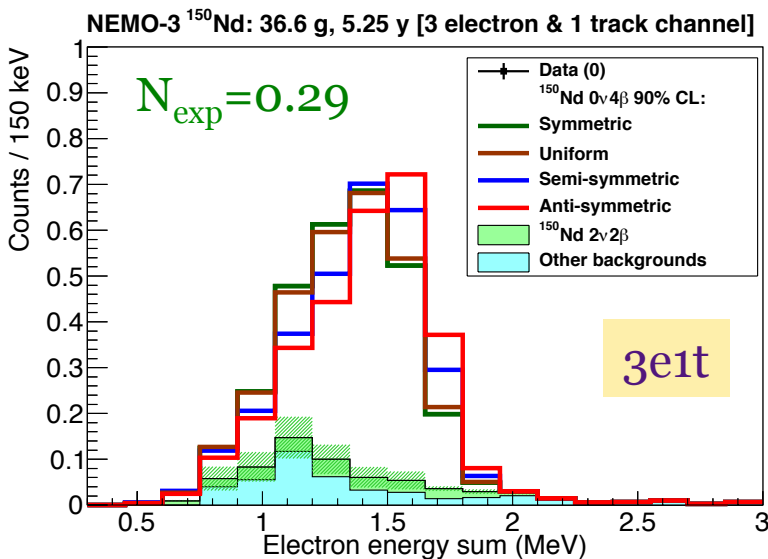
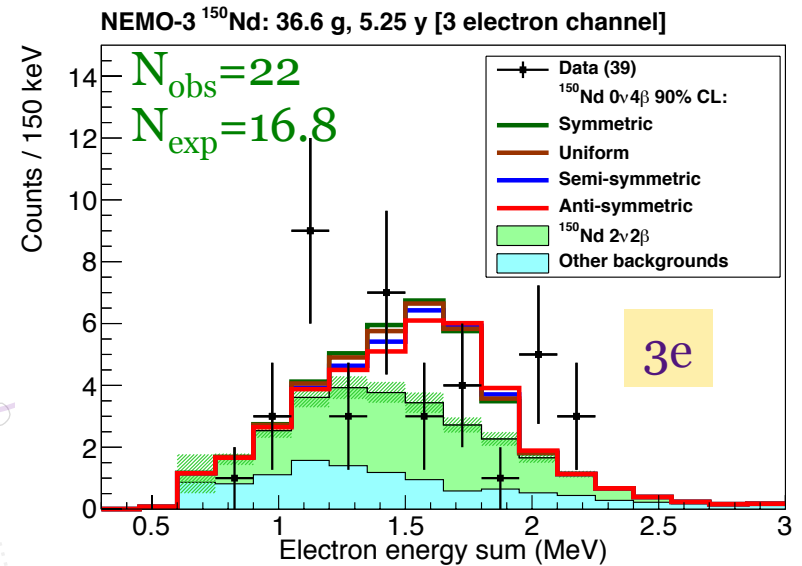


Results of the search on ^{150}Nd



(N_{exp} , N_{obs} in
[1.2, 2.0] MeV
window)

Q-value 2.08
MeV
Peaks spread
& shifted
down due to
resolution &
energy losses



- Zero events observed in 4e, 3e1t topologies
- No significant excess of data observed in 3e channel
- 4 different kinematic models of $0\nu 4\beta$ tested
 - Different efficiencies depending on how the energy is shared between electrons
 - Result is largely model independent

Systematic uncertainties

- Uncertainties on background activities described in Phys Rev D 94, 072003 (2016)
 - ~40% uncertainty on reducible backgrounds (internal & external contamination)
 - 5.5% uncertainty on $2\nu 2\beta$ background
- Uncertainties on signal:- reconstruction efficiency, model kinematics
 - Kinematics affect 4e golden channel more, due to electron loss in the foil

Source	4e	3e	3elt
Reconstruction efficiency (ϵ_{2e})	$\pm 5.5\%$	$\pm 5.5\%$	$\pm 5.5\%$
Reconstruction efficiency (ϵ_{3e})	$\pm 8.5\%$	$\pm 8.5\%$	$\pm 8.5\%$
Energy scale	$\pm 12.1\%$	$\pm 4.4\%$	$\pm 8.5\%$
Angular distribution	$\pm 5.7\%$	$\pm 1.9\%$	$\pm 4.5\%$

- However, result is statistics-dominated, systematics make only a tiny impact

First ever limit on $0\nu 4\beta$

	Symmetric		Uniform		Semi-symm.		Anti-symm.	
	obs	exp	obs	exp	obs	exp	obs	exp
4e	0.5	0.3	0.3	0.2	0.1	0.1	0.03	0.02
3e	1.6	2.4	1.5	2.1	1.2	1.7	0.9	1.2
3elt	2.0	1.9	1.5	1.4	0.7	0.6	0.3	0.3
Combined	3.2	3.7	2.6	3.0	1.7	2.0	1.1	1.3

← Different kinematic models of electron energy sharing

$$T_{1/2} > (1.1 - 3.2) \times 10^{21} \text{ years}$$

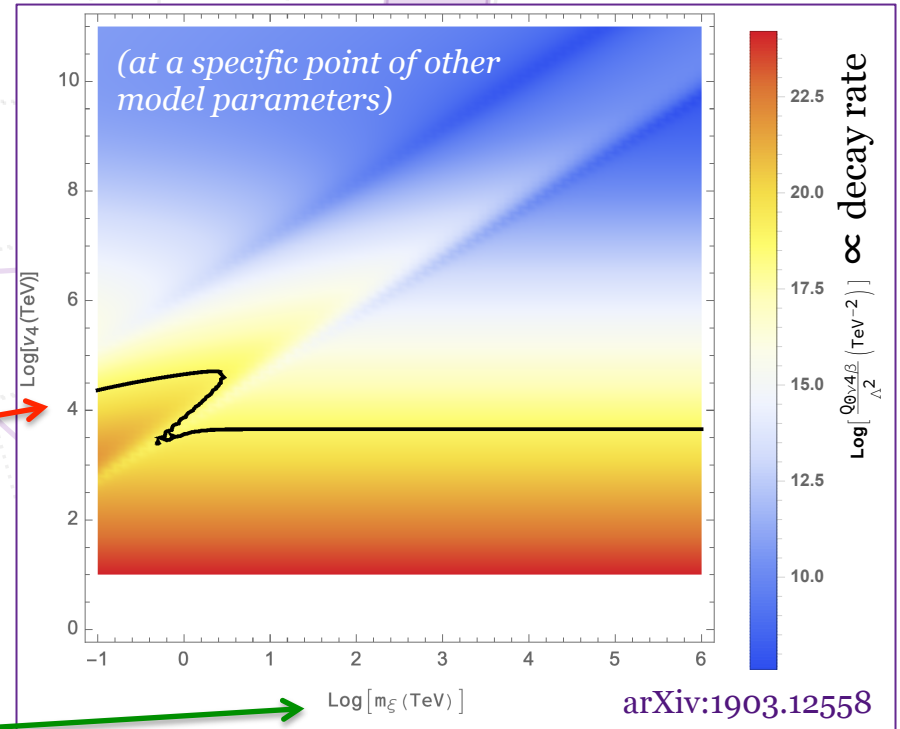
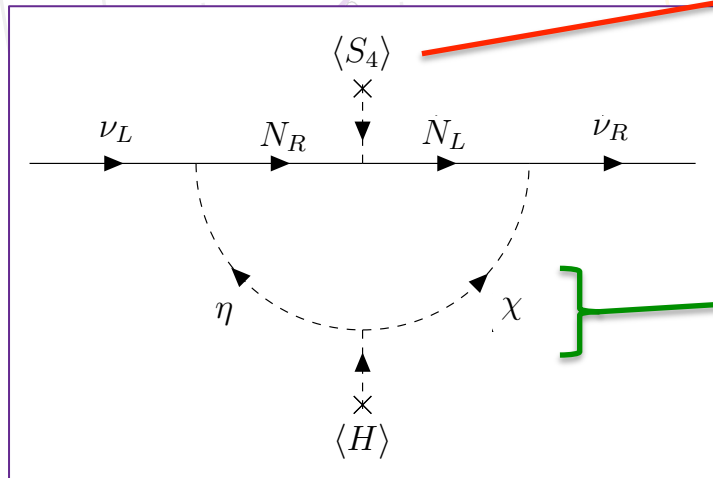
- Limit is set with a combination of all three topologies studied
- Sensitivity is mostly driven by the 3e topology, due to the $\sim 10\times$ higher efficiency
- Four different kinematic models tested
 - affecting how the energy is shared between the four electrons
 - Main dependence due to different efficiencies
- Published in PRL as an editor's suggestion:
 - **Phys Rev Lett 119 4,041801 (2017)**
- First ever limit, and still the best even after two more experiments

Setting limits on models

Earlier this year, the NEMO-3 result was used to constrain New Physics for the first time, in a radiative mass model

- Dasgupta, Kang, Popov, arXiv:1903.12558

vacuum expectation value $\langle S_4 \rangle$



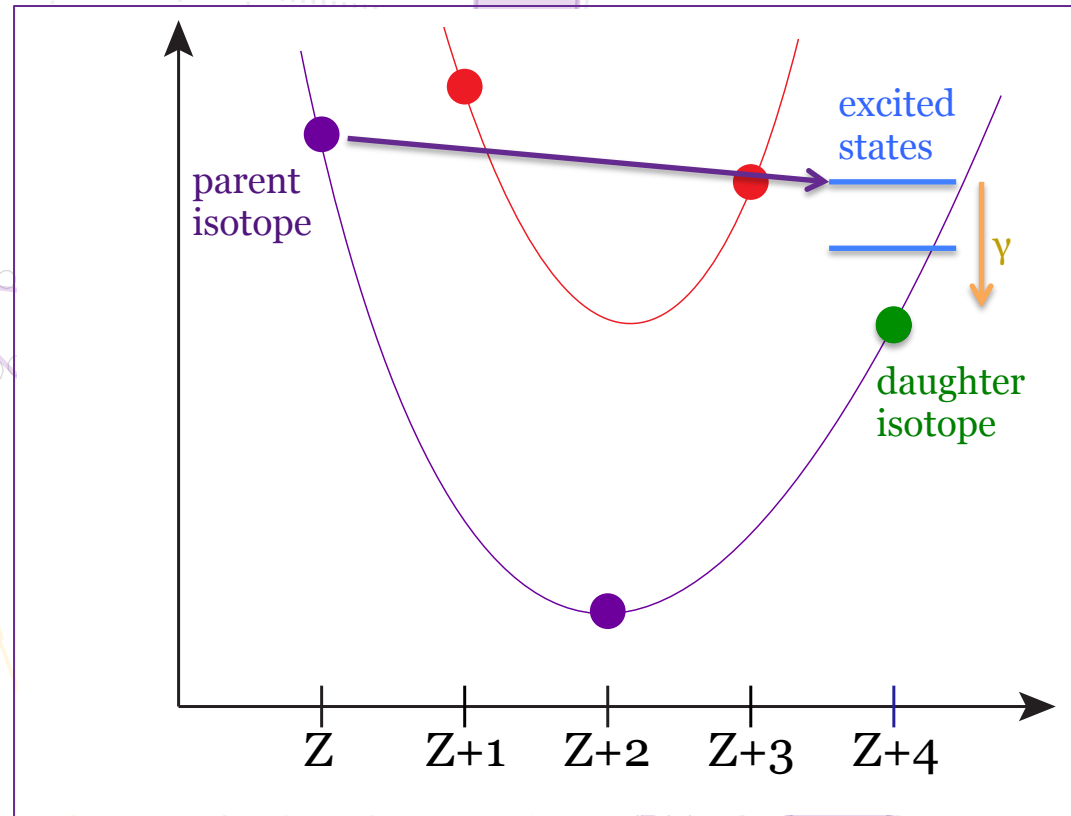
mass eigenstates of mixed η, χ

Future prospects

- SuperNEMO, successor to NEMO-3, is being commissioned now
- Initially it will not use only ^{82}Se , not a $0\nu 4\beta$ isotope
- However, O(kg) of Nd has been acquired by the collaboration
 - R&D underway enrichment and foil production
- Other experimental techniques can also be used...

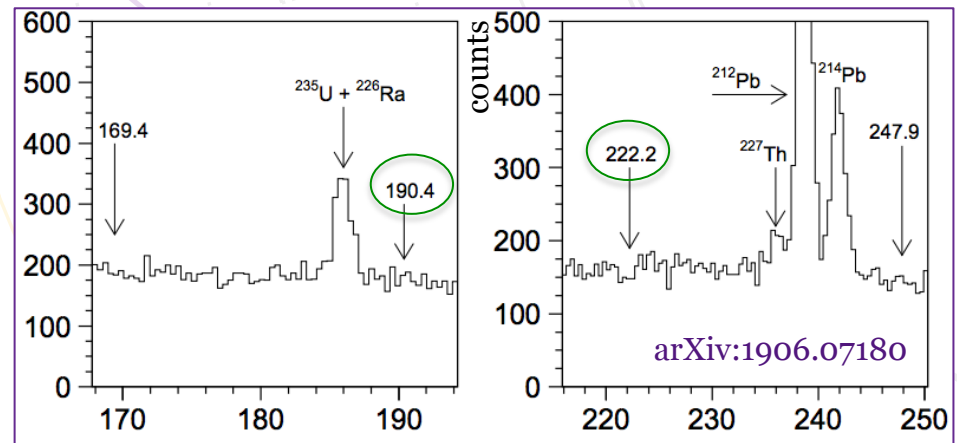
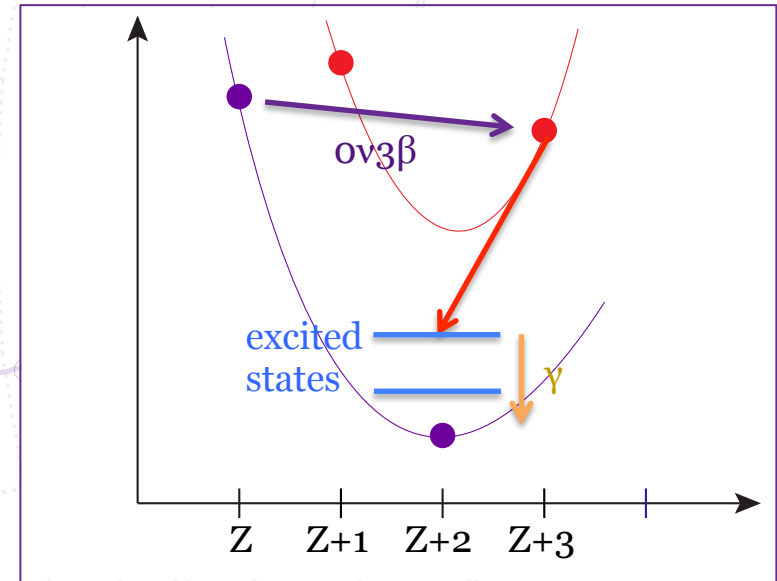
Two other search strategies

- Search for decays to **excited states**
 - γ s of specific energies
 - Kidd, Tornow, Phys Rev C98 5,055501 (2018)
 - $T_{1/2} > 2 \times 10^{20}$ years
 - Barabash, Hubert, Nachav, Umatov, arXiv: 1906.07180
 - $T_{1/2} > 8 \times 10^{20}$ years
- Search for **daughter isotope**
 - Preliminary studies for ^{96}Zr isotope – Mayer et al, Phys Rev C98 2, 024617 (2018)
 - 10^{23} year half-life sensitivity expected



Searching for triple beta decay

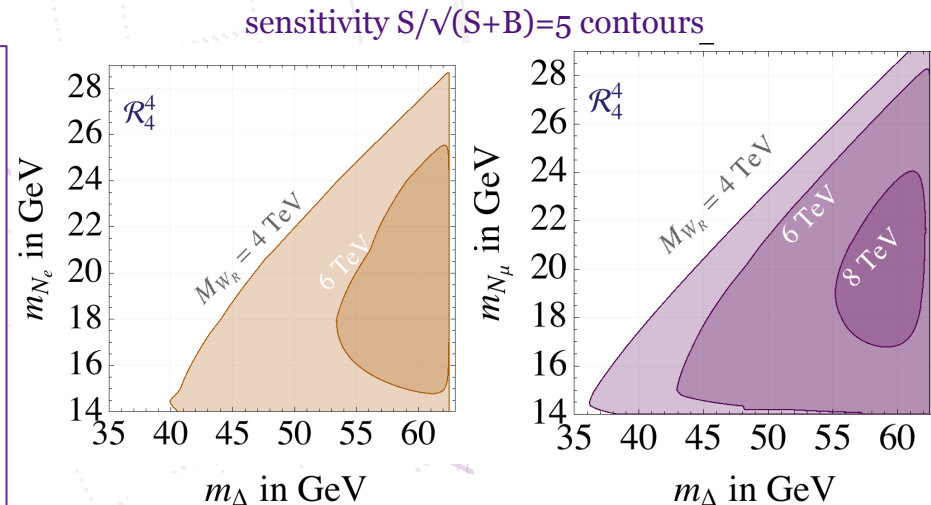
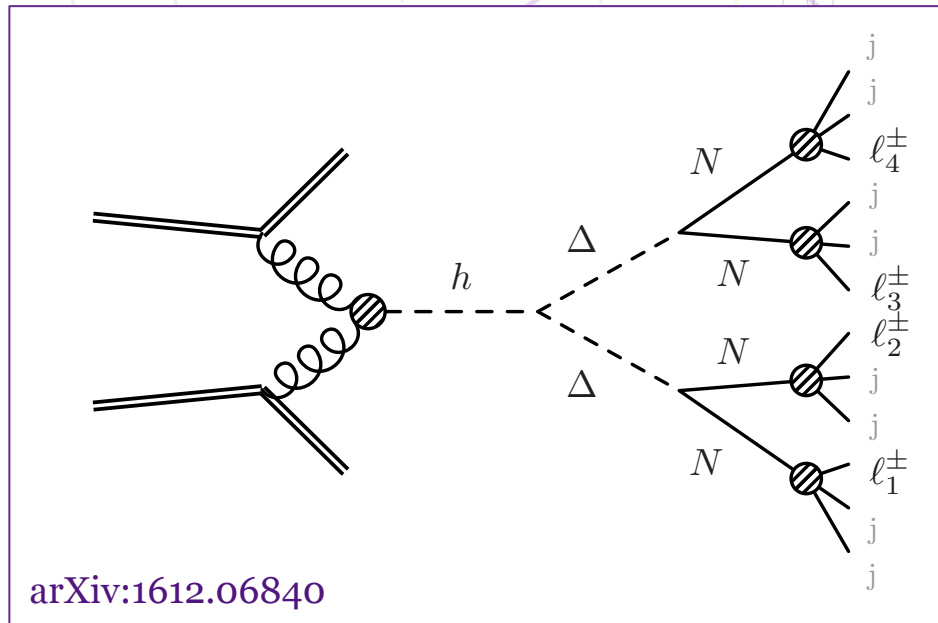
- Lorentz violating decay
- Search for β^+ decay of daughter isotope
 - Also excited state γ s
- Barabash, Hubert, Nachav, Umatov, arXiv:1906.07180
 - $T_{1/2} > 4.8 \times 10^{20}$ y
 - Coincidence of 190.4 & 222.2 keV gammas



Gamma energy spectra (keV)

Collider searches

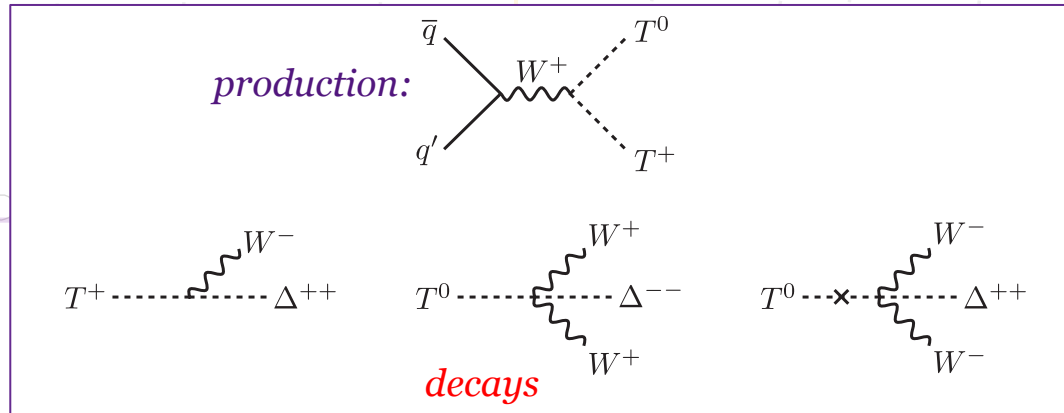
- Colliders have some chance of creating the high-mass intermediate particles involved in $\Delta L=4$ processes
 - Usual signature is production of four same-sign charged leptons



Higgs-mediated production

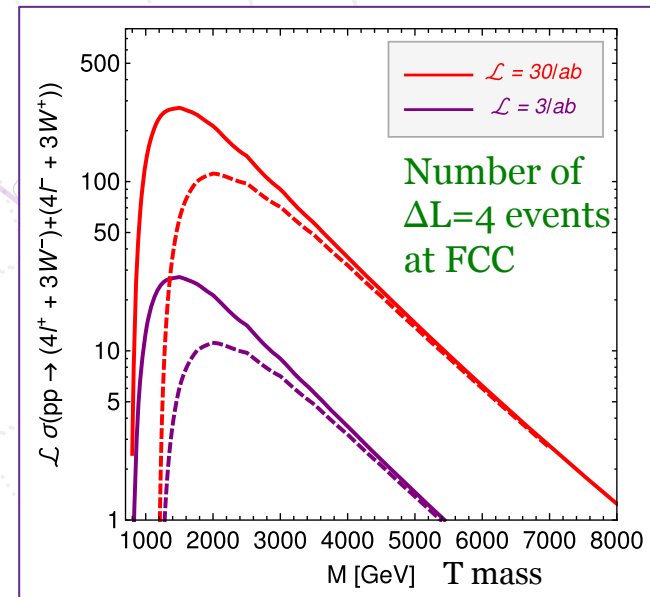
Another $\Delta L=4$ model

arXiv:1804.10545



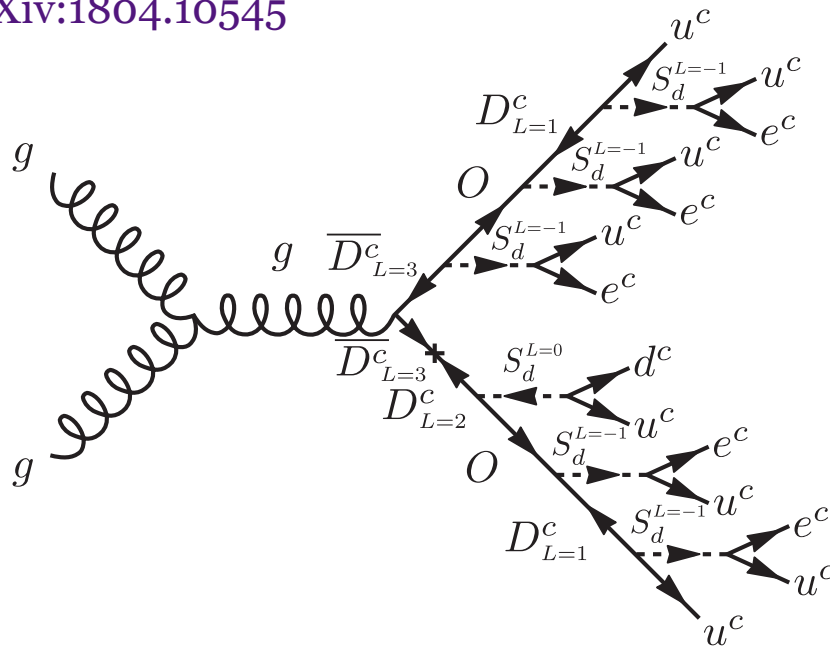
W-mediated
production

- Model introduces new scalar triplets Δ and T
- Δ eventually decays to same-sign leptons



$\Delta L=5$ at colliders

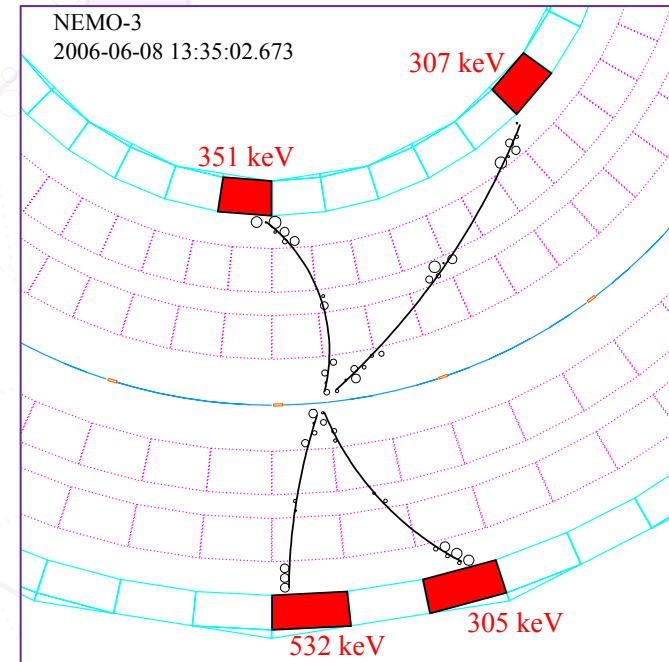
arXiv:1804.10545



- Model with $\Delta L=5$, $\Delta B=3$
 - Two new fermions O, D ; new scalar S
- 10-event sensitivity for:
 - $m_D < 2.7$ TeV in 3 ab^{-1} at LHC
 - $m_D < 13.3$ TeV in 3 ab^{-1} at FCC

Summary

- Dirac neutrinos with Lepton Number Violation are an interesting if unpopularised phenomenon to study
 - Can be related to leptogenesis & seesaw mass models just like their more famous Majorana counterparts
 - Neutrinoless quadruple beta decay is signature of such models
- Recently the NEMO-3 made the first limit on neutrinoless quadruple beta decay
 - $T_{1/2} > 3 \times 10^{21}$ years
 - Can be used to set limits on radiative mass models
 - This result has stimulated some activity into studying these models
- Rapidly evolving experimental & theoretical field



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- **“Hopeless” is too pessimistic**

